

COSMIC
NEUTRINOS
AND
MICROSCOPIC
BLACK HOLES

Jonathan Feng
University of California, Irvine

September 2002

BLACK HOLES

BH production requires “strong gravity” to change spacetime structure; masses or energies above fundamental Planck mass M_D .

$D = 4$ dimensions

- $M_D \simeq 10^{19}$ GeV
- BHs confined to astrophysics

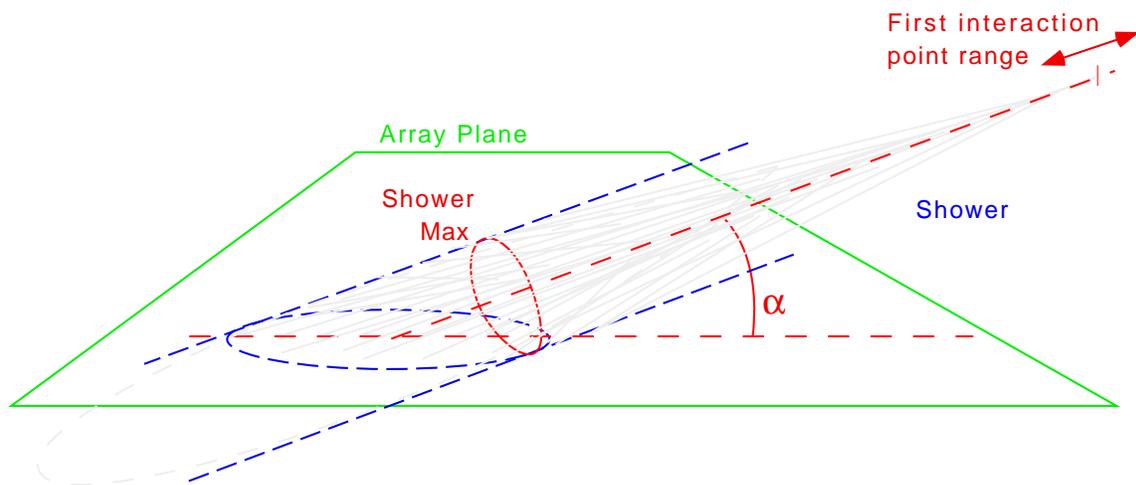
$(4+n)$ dimensions

- $M_D \approx$ TeV possible
- BHs \rightarrow experimental particle physics

(LHC: $\sqrt{s} = 14$ TeV)

Cosmic Rays: $E \gtrsim 10^{19}$ eV $\Rightarrow \sqrt{s} \gtrsim 100$ TeV

BHs \rightarrow particle astrophysics



No black holes seen \Rightarrow

- stringent bounds

$M_D \approx 1$ TeV \Rightarrow

- 100 BHs at Auger before LHC turns on
- 1st evidence for extra dimensions
- exp. study of Hawking evaporation
- Last stages of BH decay (qu. gravity)

⋮

Additional possibilities

p -branes

Warped geometries

Under-ice: AMANDA, IceCube

Radio: RICE, ANITA

Space-based: EUSO/OWL

These provide BH branching ratios, angular distributions, etc.

Feng, Shapere (2001)
Anchordoqui, Goldberg (2001)
Empanan, Masip, Rattazzi (2001)
Uehara (2001)
Ringwald, Tu (2001)
Anchordoqui, Feng, Goldberg, Shapere (2001)
Ahn, Cavaglia, Olinto (2002)
Kowalski, Ringwald, Tu (2002)
Jain, Kar, Panda, Ralston (2002)
Alvarez-Muniz, Feng, Halzen, Han, Hooper (2002)
Anchordoqui, Feng, Goldberg (2002)
Iyer Dutta, Reno, Sarcevic (2002)
Anchordoqui, Goldberg, Shapere (2002)
McKay, *et al.* (2002)
⋮

Low-scale gravity

Consider gravity in $(4+n)$ dimensions,
SM in 4 dimensions.

Compactification in n flat dimensions with length
 L gives

$$F \sim \begin{cases} G_N \frac{m_1 m_2}{r^2}, & r \gg L \\ \frac{m_1 m_2}{M_D^{2+n} r^{2+n}}, & r \ll L \end{cases}$$

Observed gravitational strength \Rightarrow

$$M_D^{2+n} L^n \approx (10^{19} \text{ GeV})^2$$

Gravity is weak because

(a) $M_D \sim 10^{19} \text{ GeV} \gg 1 \text{ TeV}$ ($n = 0$)

(b) $M_D \sim 1 \text{ TeV}$, but L large in Planck units.

Arkani-Hamed, Dimopoulos, Dvali (1998)

BHs in extra dimensions

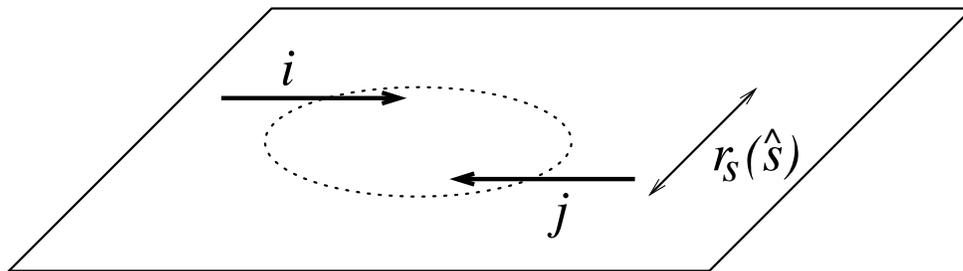
For a Schwarzschild BH ($Q = J = 0$),

$$r_s(M_{\text{BH}}^2) = \frac{1}{M_D} \left[\frac{M_{\text{BH}}}{M_D} \right]^{\frac{1}{1+n}} \left[\frac{2^n \pi^{\frac{n-3}{2}} \Gamma\left(\frac{3+n}{2}\right)}{2+n} \right]^{\frac{1}{1+n}}$$

Myers, Perry (1986)
Argyres, Dimopoulos, March-Russell (1998)

In classical GR, expect a BH to form when two partons pass within $r_s(\hat{s})$ of each other:

$$\hat{\sigma}(ij \rightarrow \text{BH})(\hat{s}) \approx \pi r_s^2(\hat{s})$$

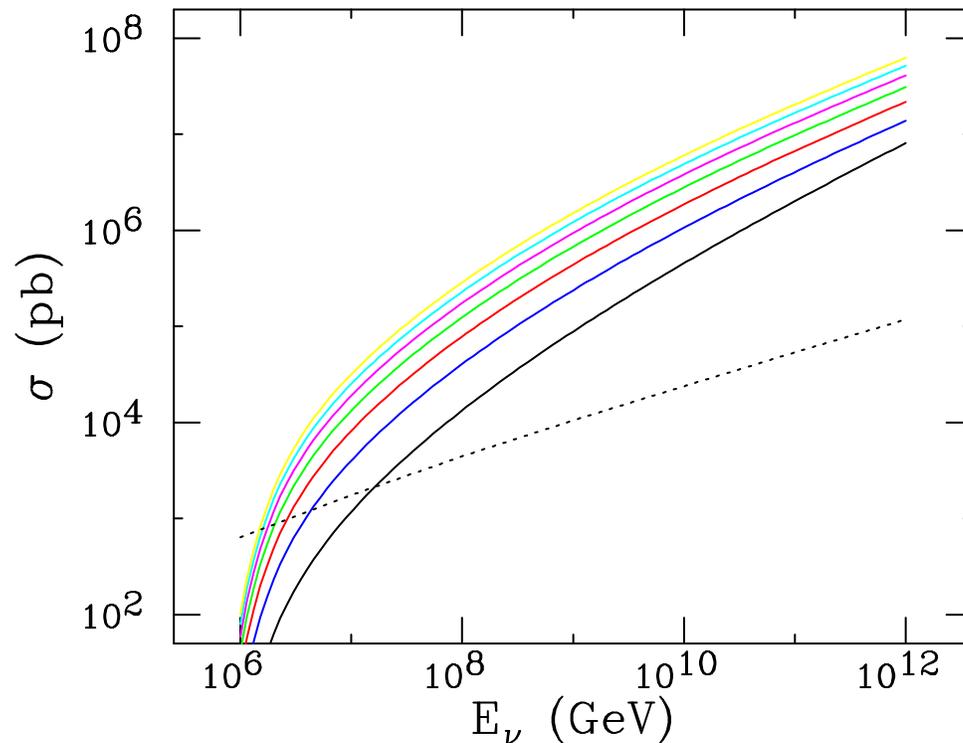


Banks, Fischler (1999) Emparan, Horowitz, Myers (2000)
Giddings, Thomas (2001) Dimopoulos, Landsberg (2001)

πr_s^2 requires $x_{\text{min}} \equiv M_{\text{BH}}/M_D \gtrsim$ a few.

Cosmic Neutrinos

$$\sigma(\nu N \rightarrow \text{BH}) = \sum_i \int_{(M_{\text{BH}}^{\text{min}})^2/s}^1 dx \hat{\sigma}_i(xs) f_i(x, Q)$$



For $M_D = M_{\text{BH}}^{\text{min}} = 1 \text{ TeV}$ and $n = 1, \dots, 7$ from below.

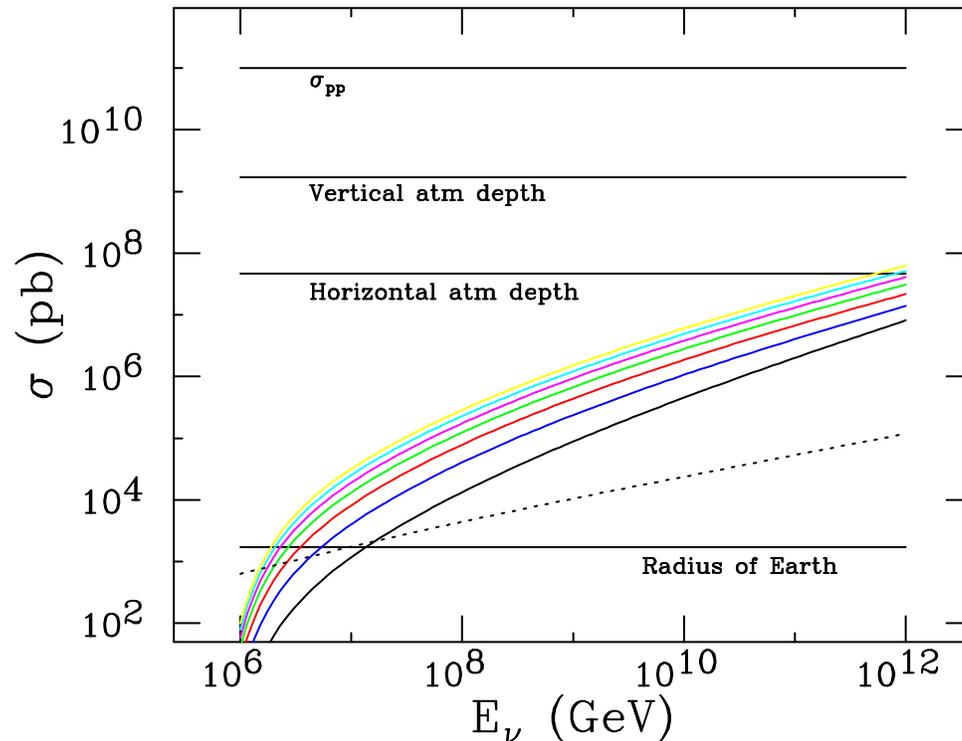
JF, Shapere (2001)

σ large:

- Sum over partons, including gluon
- No small couplings
- ν has $x = 1$

Relatively insensitive to $M_{\text{BH}}^{\text{min}}$ (see below).

Length scales



Vertical atm. depth: 10 mwe

Horizontal atm. depth: 360 mwe

• $pN \rightarrow \text{BH}$: Hopeless

• $\nu N \rightarrow \text{BH}$: uniform at all atm. depths

Best signal is quasi-horizontal, deep showers:
maximizes signal, uses atmosphere to remove
proton, nucleus background.

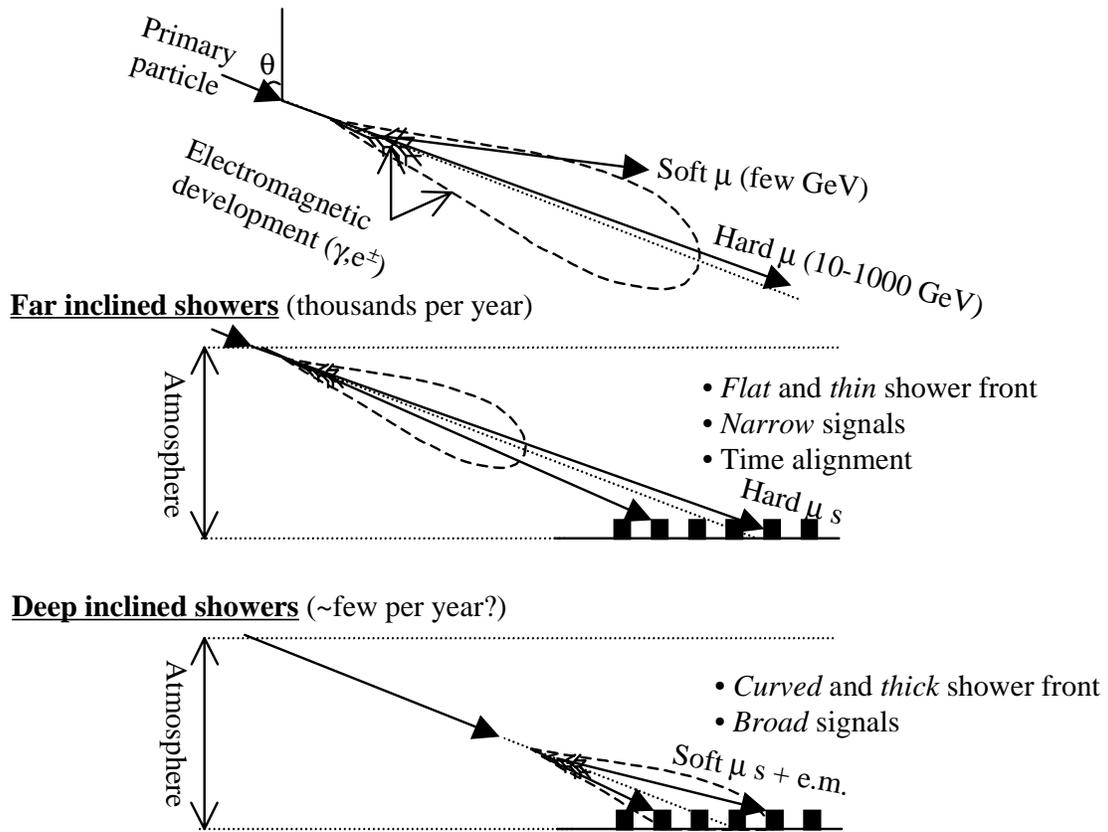


FIG. 6. Schematic representation of a UHE air shower, and of its placement with respect to the ground and the Auger array. A “far inclined” shower is likely to be due to a hadronic cosmic ray, whereas a “deep inclined” shower can only be caused by a neutrino.

Coutu, Bertou, Billoir (1999)

Rates

$$\mathcal{N} = \int dE_\nu N_A \frac{d\phi}{dE_\nu} \sigma(E_\nu) A(E_\nu) T$$

where

$$N_A = 6.022 \times 10^{23}$$

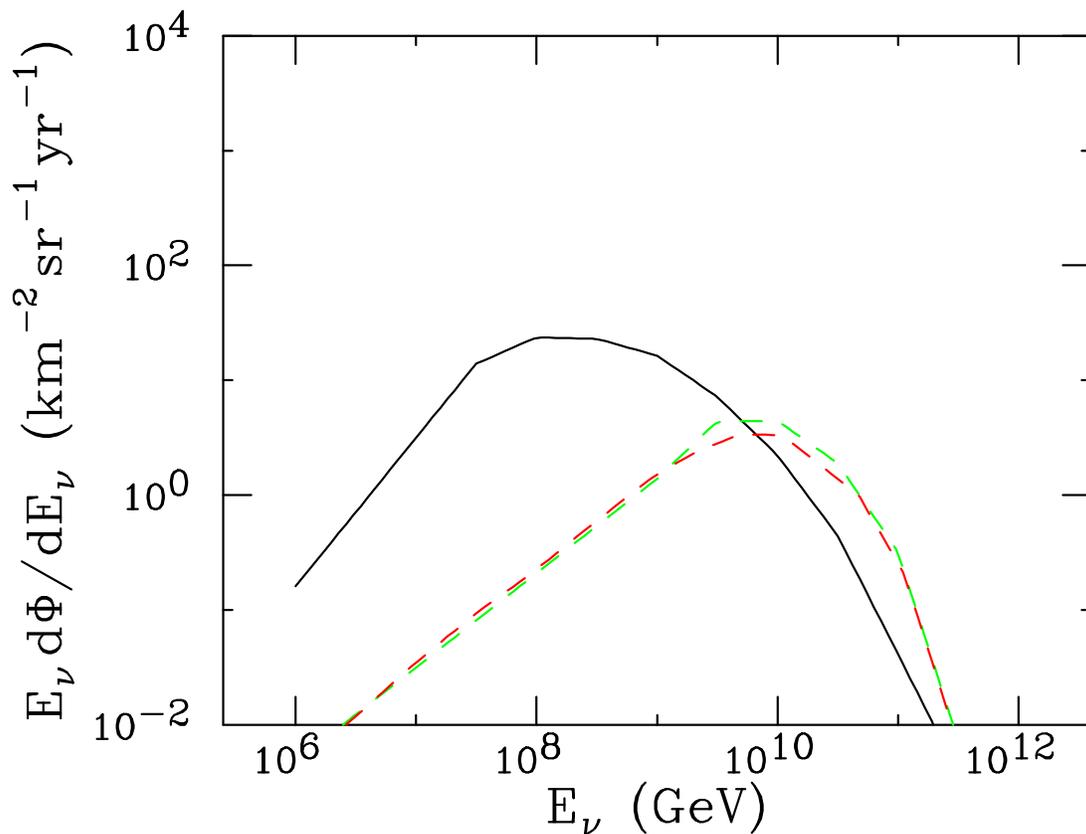
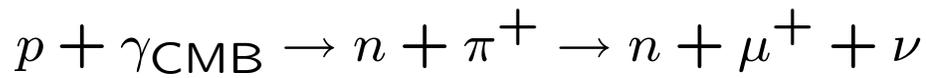
$$\frac{d\phi}{dE_\nu} = \text{source flux of neutrinos}$$

$$A = \text{acceptance in cm}^3\text{we}$$

$$T = \text{running time of experiment}$$

Fluxes

Guaranteed: π photoproduction



Stecker (1979)

Hill, Schramm (1985)

Protheroe, Johnson (1996)

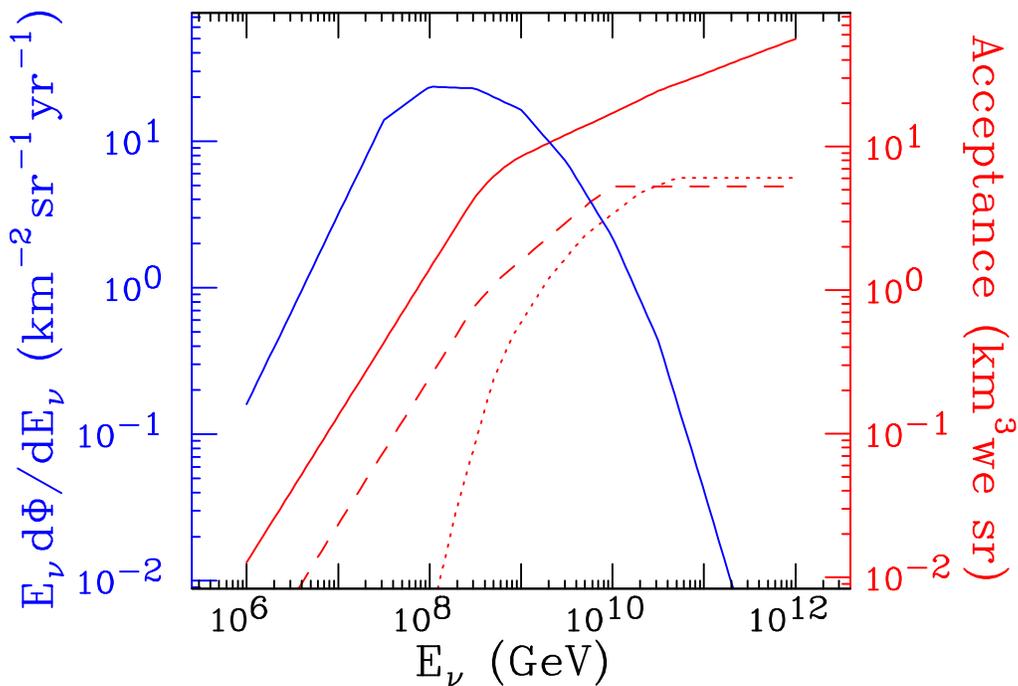
Choose most conservative: Protheroe, Johnson.

Apertures

Showers may be detected by ground arrays and air fluorescence.

Current: AGASA, Hires

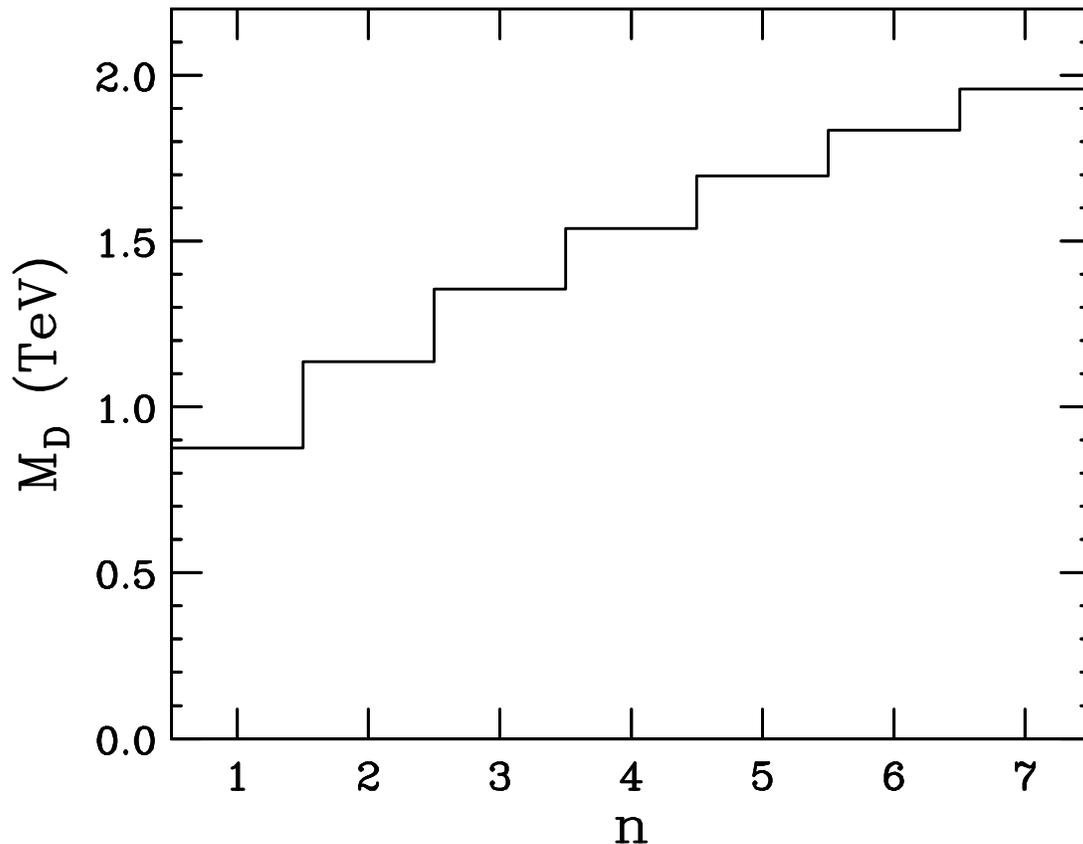
Future: Pierre Auger Observatory



Quasi-horizontal shower acceptance for Auger ground array (solid), AGASA (dashed), Hires (dotted).

Capelle, Cronin, Parente, Zas (1998)
Diaz, Shellard, Amaral (2001)
Anchordoqui, JF, Goldberg, Shapere (2001)
Hires Collaboration (1994)

Current Bounds: AGASA, Hires

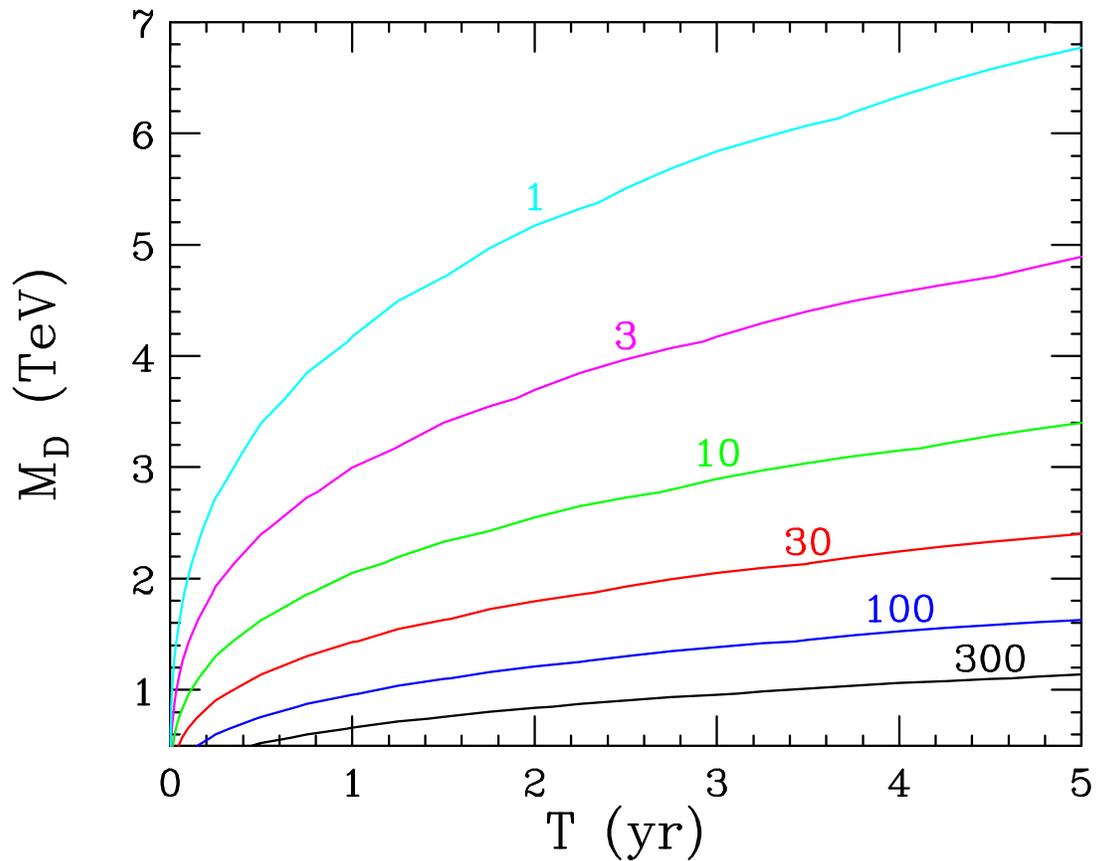


Lower bounds on M_D from absence of black holes at AGASA and Hires. $M_{\text{BH}}^{\text{min}} = M_D$.

Anchordoqui, JF, Goldberg, Shapere (2001)

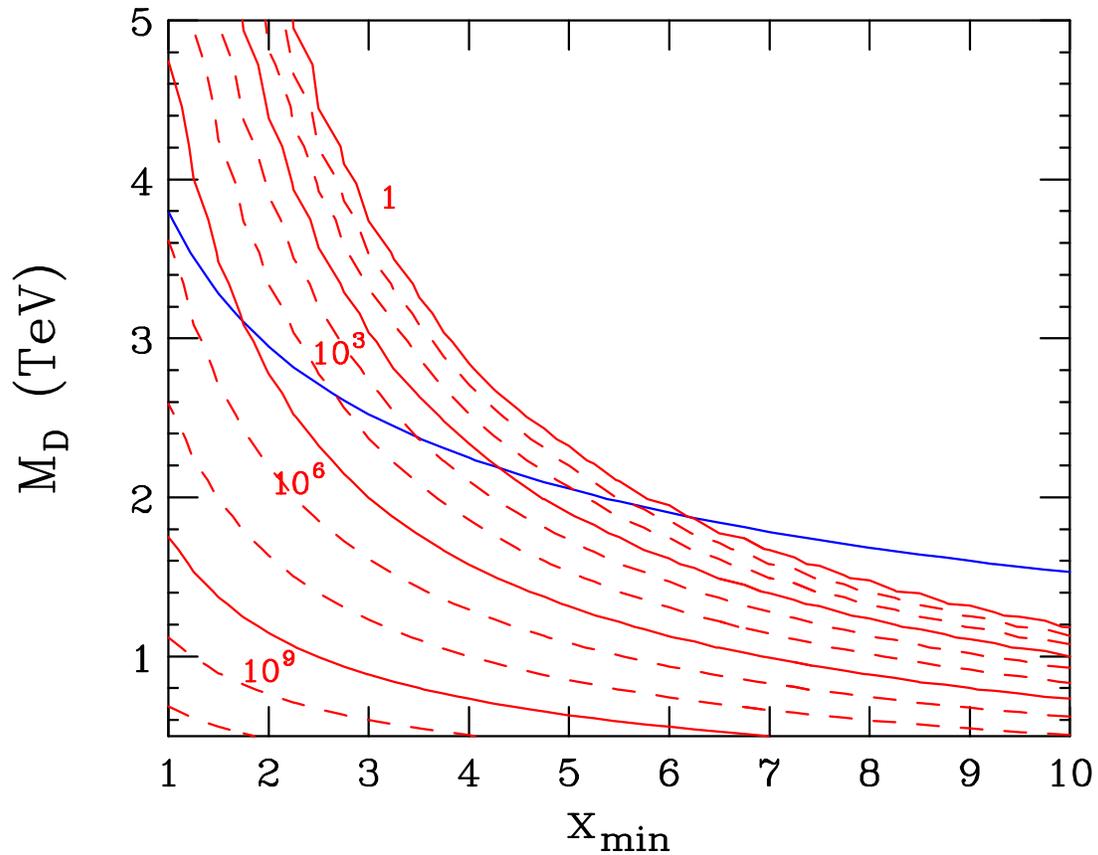
No events seen \Rightarrow for $n \geq 4$, $M_D \gtrsim 1.5\text{--}2.0$ TeV, most stringent bounds to date.

Future Prospects: Auger



Number of black holes expected at the Auger ground array for $n = 7$. $M_{\text{BH}}^{\text{min}} = M_D$.

Comparison with LHC



Auger sensitivity (3 years)

LHC events (100 fb^{-1})

$n = 7$.

- LHC predictions sensitive to M_{BH}^{\min}
- No Auger BHs, $x_{\min} \gtrsim 5 \Rightarrow$ No LHC BHs

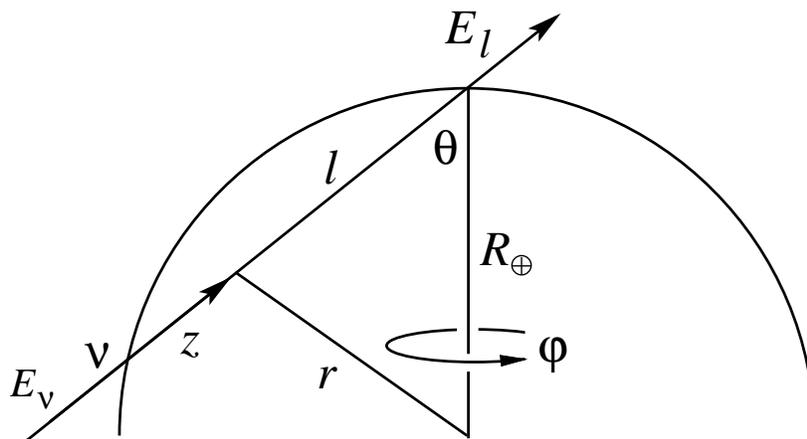
Of course, we could see events! ...

BH vs. SM

BH rates may be 1000 times SM rate. But

- large BH $\sigma \Rightarrow$ large rate, and
- ϕ large \Rightarrow large rate.

However, consider Earth-skimming neutrinos:



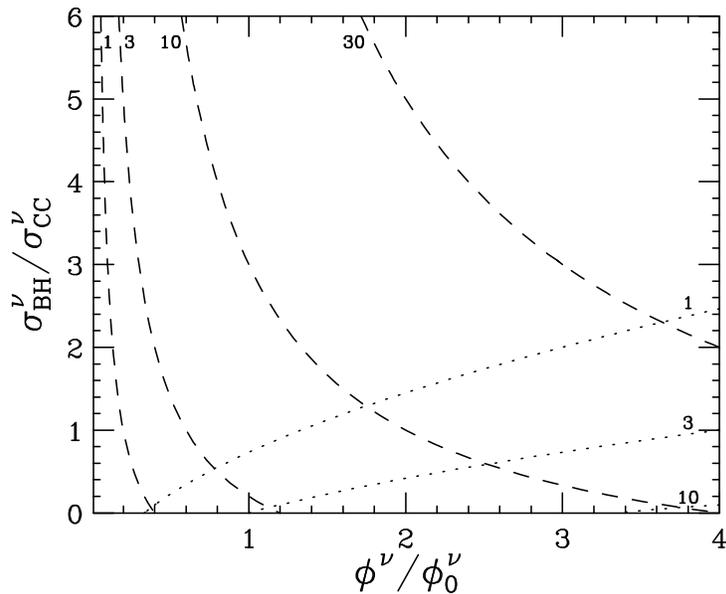
Bertou *et al.* (2001)
JF, Fisher, Wilczek, Yu (2001)

For Earth-skimmers,

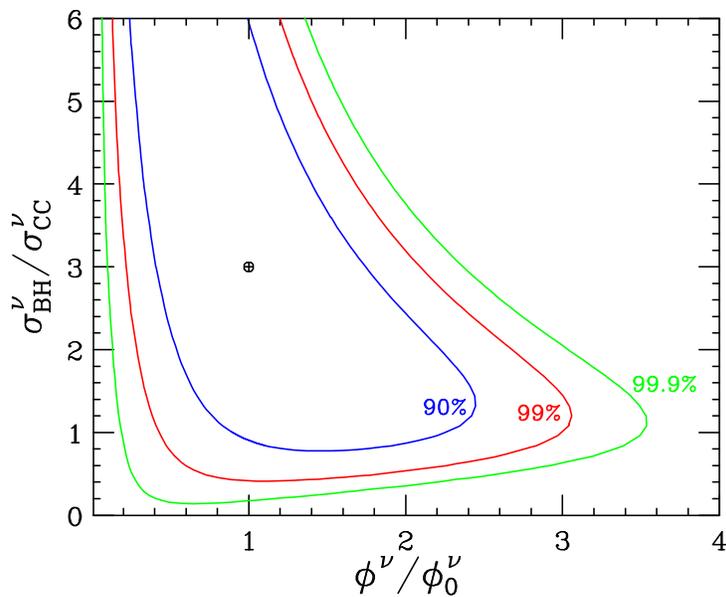
- ϕ large \Rightarrow large rate, but
- large BH $\sigma \Rightarrow$ rate suppressed

Rates alone eliminate SM explanation (and almost all other non-SM explanations, too).

$$N_{\text{QH}} \propto \phi^\nu (\sigma_{\text{CC}}^\nu + \sigma_{\text{BH}}^\nu) \quad N_{\text{ES}} \propto \phi^\nu \frac{\sigma_{\text{CC}}^{\nu 2}}{(\sigma_{\text{CC}}^\nu + \sigma_{\text{BH}}^\nu)^2}$$



Quasi-horizontal shower (dashed) and Earth-skimming neutrinos (dotted) in 5 years.



BH signatures

BH rest lifetime is

$$\tau \sim \frac{1}{M_D} \left[\frac{M_{\text{BH}}}{M_D} \right]^{(3+n)/(1+n)} \sim 10^{-27} \text{ s}$$

Even with boost $\gamma \sim 10^7$, all BHs evaporate effectively instantaneously.

BH temperature is ~ 100 GeV.

Average multiplicity is

$$\langle N \rangle \approx \frac{M_{\text{BH}}}{2T_H} \propto \left[\frac{M_{\text{BH}}}{M_D} \right]^{\frac{2+n}{1+n}}$$

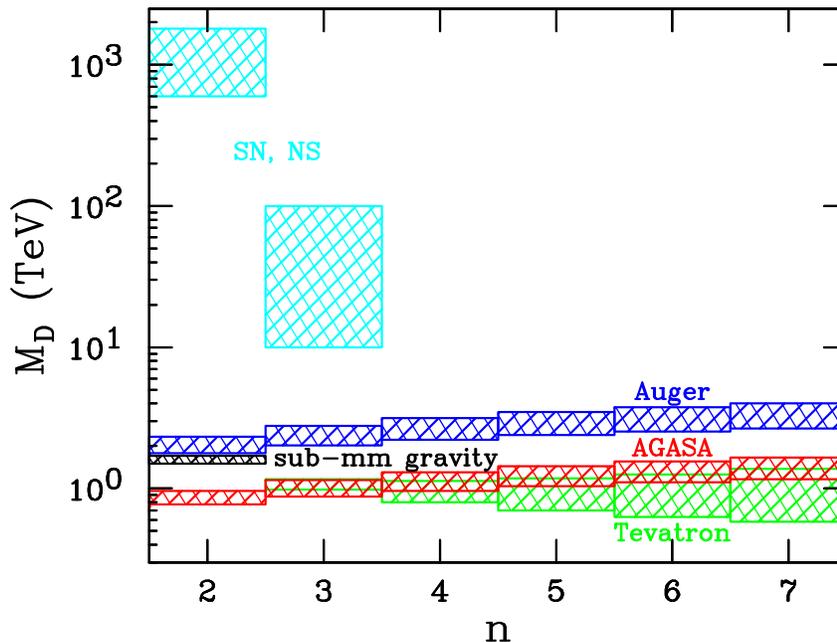
leptonic : hadronic $\simeq 1 : 5$

In contrast,

$$\begin{aligned} \nu_e N \rightarrow e X &\Rightarrow \text{EM (80\%)} + \text{hadronic (20\%)} \\ \nu_\mu N \rightarrow \mu X &\Rightarrow \text{nothing} + \text{hadronic (20\%)} \end{aligned}$$

CONCLUSIONS

- BHs: a rare opportunity to consider super-Planckian energies.
- Naturally probed at the energy frontier: UHE Cosmic Rays
- Constraints on TeV gravity:



- $M_D \approx 1$ TeV \Rightarrow 100 BHs at Auger